An Investigation into the Relationship between Ionospheric Scintillation and Loss of Lock in GNSS Receivers

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ABSTRACT

Irregularities in the ionospheric electron density can cause a phenomenon known as scintillation, in which the phase and amplitude of transiting radio signals fluctuate rapidly. Scintillation can have an adverse effect on Global Navigation Satellite Systems (GNSS) signals as they pass from a satellite to a receiver, and extreme cases can cause a GNSS receiver to lose lock on the signal. This limits the availability of path-length measurements, and compromises the integrity of the navigation solution. Scintillation is not, however, the only mechanism that can cause a receiver to lose lock on a signal. For example, local multipath and shadowing can also contribute to the loss of phase lock.

In this work, we examine the correlation between phase and amplitude scintillations and loss of phase-lock events in co-located GPS receivers to establish whether loss-of-lock is associated with scintillation or multipath. One phase and amplitude scintillation receiver was deployed at each of the three European Incoherent Scatter (EISCAT) radar sites in Northern Scandinavia in the summer of 2004, and they have since provided an ongoing data record. In this paper we focus on the ionospheric storm period of November 2004. Using scintillation data from these receivers in conjunction with GPS observation data from the IGS receivers at Tromsø, Kiruna and Sodankylä, we attempt to identify those losses of phase lock for which scintillation was the cause, and distinguish them from losses of phase lock caused by local multi-path and shadowing effects.

1.0 INTRODUCTION

The Global Positioning System (GPS) is the first Global Navigation Satellite System (GNSS) to be widely available to civilian users, and has been adopted successfully for many different applications. However, there remains a number of critical problems with using GPS for applications requiring a high degree of accuracy and integrity. These problems originate in uncertainties in the signal's propagation speed and path, and are related to atmospheric phenomena and local environment factors. In this paper we are concerned with uncertainties due to atmospheric phenomena. In particular, we examine the effects of the ionised regions of the atmosphere over Europe.

The GPS satellites transmit the navigation message on two L-band frequencies: 1.575 and 1.228 GHz, known respectively as L1 and L2. The ionosphere is a dispersive medium, and so the ionospheric delay can be estimated using dual-frequency receivers. However, single frequency receivers cannot do this and must therefore rely on a model. Under conditions of high geomagnetic activity, significant limitations to the accuracy of single frequency receivers are posed by the inaccuracy of the model. In extreme cases, the

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ionospheric delay along a single path could be over 200 TEC units vertically [1], which corresponds to about 20 m for a satellite overhead. This can rise to three times this amount for one at low elevation. More conservative estimates from an ionospheric model [2] indicate that the resulting effect on the user location could be several metres, with the error most strongly affecting the vertical position. There are currently a number of ionospheric correction systems under test in Europe, the USA [3] and Japan, the purpose of which are to provide real-time ionospheric corrections for civil aircraft navigation.

The ionosphere can also have an effect on the integrity (i.e. availability) of a GNSS system at certain locations. GNSS operations can be hampered when the signals pass through the auroral oval by scintillation. This can lead to loss of lock on the signal, limiting the availability of carrier-phase measurements. Even larger effects are experienced on the lower GPS frequency (L2), which needs sophisticated codeless tracking algorithms in order for it to be monitored. The physical causes behind these rapid fluctuations in signal amplitude and phase (scintillations) are small-scale irregularities in electron concentration in the ionosphere. One mechanism to create these is by the precipitation of particles in the auroral regions (nominally around 67°N) that results in a range of small-scale structures that can cause scintillation of L-band signals. Space-weather disturbances, resulting in ionospheric storms, cause the expansion of the auroral oval and move ionospheric structures equatorward.

In this paper, we examine the correlation between phase and amplitude scintillations, and loss of phase-lock events in co-located GPS receivers to establish whether loss-of-lock is associated with scintillation or multipath. The focus of this study is the ionospheric storm period of November 2004. Associated with this storm period is an isolated rapid signal fading event. The S4 index, which is a measure of the amplitude scintillation over one minute, does not characterise fades of short duration. Nevertheless, such fades are present in the raw data, and have an adverse effect on the reliability of a signal link. The fade was observed on the link to PRN 5 at around 0123 UT on 8 November 2004, at three closely sited GPS scintillation receivers in northern Norway. The spacing of the receivers is such as to allow the velocity of the ionospheric structures to be estimated, and, given an assumed height, this corresponds to a fast-moving auroral arc. Such a feature was also observed in All-Sky Camera (ASC) images.

2.0 METHOD

Three Novatel GSV4004 [4] phase and amplitude scintillation receivers were deployed in Northern Scandinavia during the summer of 2004. Measurements of phase and amplitude scintillation from these receivers have been archived since then, and are available for analysis. The receivers are fitted with high-precision oven-controlled oscillators that enable them to sample the code and carrier phase path lengths on the L1 and L2 carrier frequencies at a rate of 50 Hz. They are installed at the three mainland European Incoherent Scatter Radar (EISCAT) sites, located at Tromsø (69.586453N, 19.227428E), Kiruna (67.860658N, 20.435222E) and Sodankylä (67.363683N, 26.627081E). This places them under the Auroral Oval. There are also fixed GPS receivers of the International GPS Service (IGS) network located near each of these positions. Observation data for the IGS receivers are freely available by FTP download from www.sopac.ucsd.ac in `RINEX' format. In addition, two amplitude scintillation receivers, developed by Cornell University, were deployed at the Tromsø site. All receivers were networked to enable routine data collection at Bath. Further observation data in RINEX format for the IGS receivers `trom', `tro1', `kiru', `kir0' and `soda' was downloaded from the SOPAC archive as required.

The phase-lock losses and their time indices were identified for the November 2004 storm using the following approaches. In the Novatel receivers, the cumulative L1 and L2 lock times, for each satellite in view, are available from the receiver logs, which are updated every 60 seconds. By double-differencing consecutive records, losses of lock appear as non-zero values, and the time index can be noted. Losses of phase-lock in the Novatel data were noted to be rare, occurring mainly on the L2 frequency. Data from the IGS receivers is in RINEX format, which does not indicate loss of phase-lock explicitly, so losses of lock must be determined by post-processing [5, 6]. Here, a simple approach was taken. The 'ionosphere-free' phase combination (sometimes referred to as the L4 combination) was computed using the following formula

$$L4 = \left(\frac{\Phi_1}{154} - \frac{\Phi_2}{120} \right) \frac{c}{10.23} \tag{1}$$

where Φ represents the phase path, the subscripts 1 and 2 represent the GPS carrier frequency (L1 or L2), and *c* is the velocity of light. A local gradient was then computed in a 10-point window based on a running median. This was compared to a threshold value to determine the time indices of the phase jumps. An elevation mask of 35° was imposed on the observation data to screen out any multipath effects.

3.0 RESULTS AND DISCUSSION

In this section, the results for the eight days covering the period from 7-Nov-2004 to 14-Nov-2004 inclusive are presented. During this period, the Kp index in the daytime increased from about 2 to over 8 between 8th Nov and 11th Nov. Results from the rapid fade event study are also presented.

The total number of L1 and L2 cycle slips on all receiver-to-satellite paths were counted for each of the three Novatel receivers and the five IGS receivers over time periods of 10, 20, 30, 40 and 60 minutes, giving a total of 40 data sets. In each case, the number of cycle slips can be seen to increase during the storm period, as expected. The Novatel receivers exhibited up to six cycle slips per hour, whilst the IGS receivers exhibited up to 16 per hour (on all receiver to satellite paths).

The correlation between the number of cycle slips in groups of receivers was investigated. First, the three Novatel receivers were considered, and it was found that the number of cycle slips correlates reasonably well, i.e. when one receiver loses lock there is a good chance that the others will (see Figure 1). This is particularly true for the longer count periods. Since these receivers are identical but independent of each other, it is reasonable to suppose that irregularities that extend across large regions of the ionosphere are contributing to these loss of lock events.

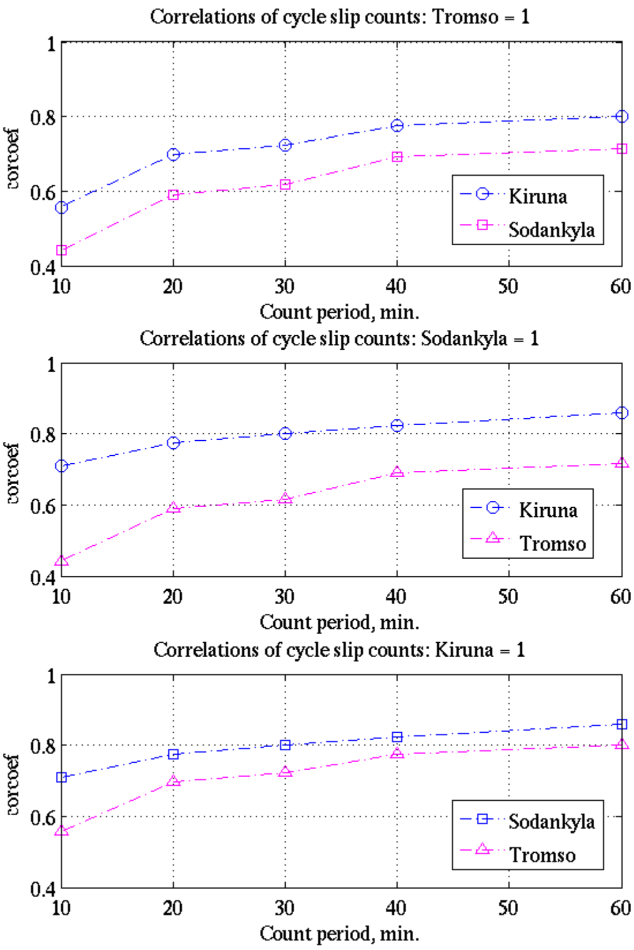

Figure 1: Cycle-slip correlations between the Novatel receivers.

The cycle slips on the five IGS receivers were correlated in a similar fashion – see figure 2. Strong correlation, about 0.97, was observed between `trom' and `tro1', which are separated by about 200 m. The same receiver type (AOA Benchmark - see the site logs at www.sopac.ucsd.ac) is used at both sites. `kiru' and `kir0' are separated by about 5 km, so it might be expected that they would correlate quite well, about 0.71. It is interesting to note that `kiru' and `soda', which are about 235 km apart, also correlate well (about 0.77). In November 2004, the receiver at `kiru' was an Ashtech UZ-12, and that at `soda' was an Ashtech Z-X113 (from the site logs). However, the receiver at `kir0' was a JPS E-GGD. This suggests that the tracking loops in the Ashtech receivers have a broader bandwidth than that of the JPS receiver, and so they are more able to accommodate the phase fluctuations. An attempt was made to establish the actual bandwidths for these receivers, but to date this has not been successful.

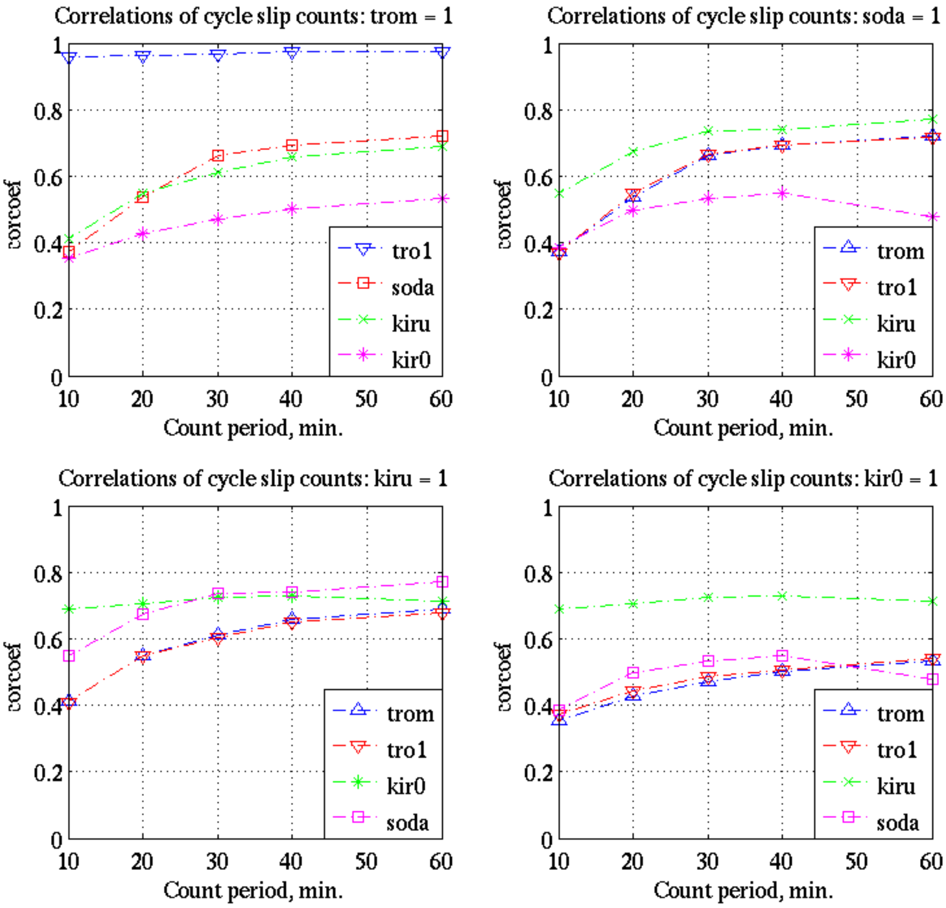

Figure 2: Cycle-slip correlations between the IGS receivers.

The correlation between the cycle-slips in each of the Novatels and their nearest IGS receivers was found to be weaker. The `soda' receiver is about 12 km north west of the Sodankyla receiver; `trom' and `tro1' are about 200 m apart and located about 14 km north west of the Tromso receiver; and `kiru' and `kir0' are about 5 km apart and located 22 km and 26 km respectively east of the Kiruna receiver. It would appear that, unless the receivers are very close (as in the case of `trom' and `tro1'), the separation of the receivers has little influence on the correlation, and the correlation between the cycle-slip counts is dominated by receiver type.

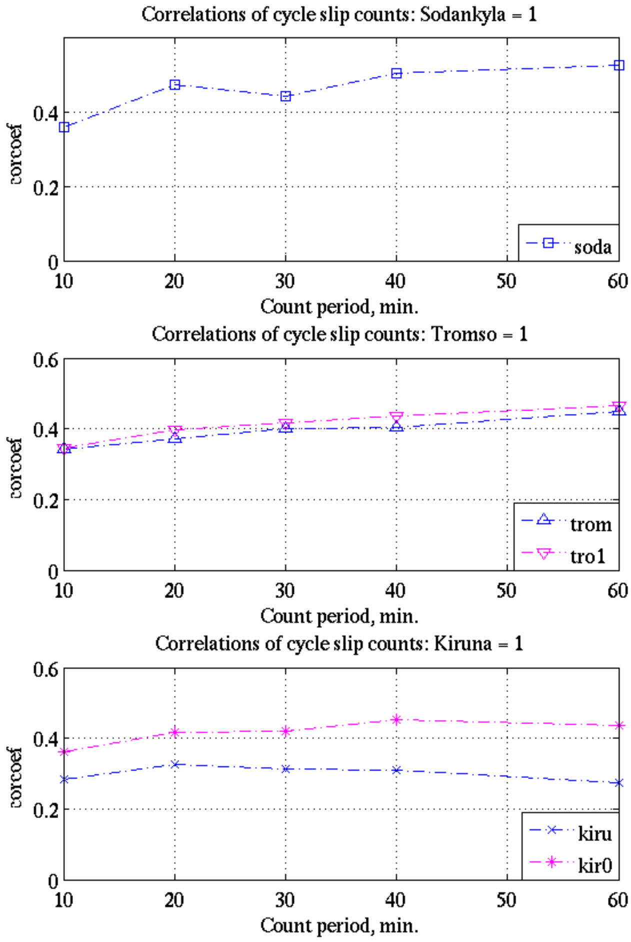

Figure 3: Cycle-slip correlations between the Novatel receivers and their local IGS receivers.

The phase (σ_φ) and amplitude (corrected s4) scintillation measurements were then extracted from the data logs of the three Novatel receivers. The maximum σ_φ and s4 for each hour and for all receiver to satellite paths were then determined and correlated with the number of cycle slips on each of the IGS receivers. The correlation coefficients are shown in Figure 4, in which it can be seen that the correlations between loss of lock and corrected s4 are quite weak. The correlation with σ_φ is a little stronger.

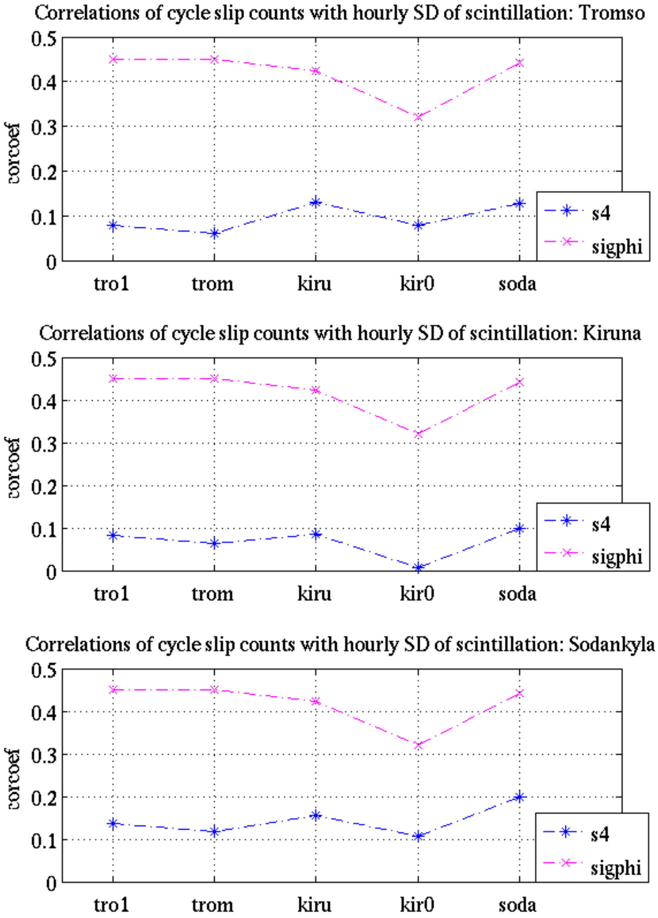

Figure 4: Correlations between the scintillation measured by the Novatel receivers and number of cycle-slips in the IGS receivers.

Figure 5 shows the fading pattern for each set of GPS receiver data. In the upper and middle plots, the signal strength for the co-located receivers reveal almost identical patterns of fading, giving confidence that the effect is external to the receivers and not due to equipment malfunction. The lower plot shows the signal strength from the same one-minute period, and reveals a slightly different fading pattern in which the onset of the event is in fact slightly earlier than for the co-located receivers. The data showed very similar fade patterns on each receiver, with a time offset in the occurrence between the co-located receivers and the other receiver based to the west. As there are effectively only two receiver locations, since two are in close proximity, only a single velocity component could be calculated. This was calculated by cross-correlating the fade pattern from each set of receiver data to determine the time offset between sites. The position and velocity components of the signal fades in the receiver data were projected along the satellite-receiver path onto the ionosphere to find the east-west velocity component at a range of hypothetical shell heights (for shells of constant altitude above the earth).

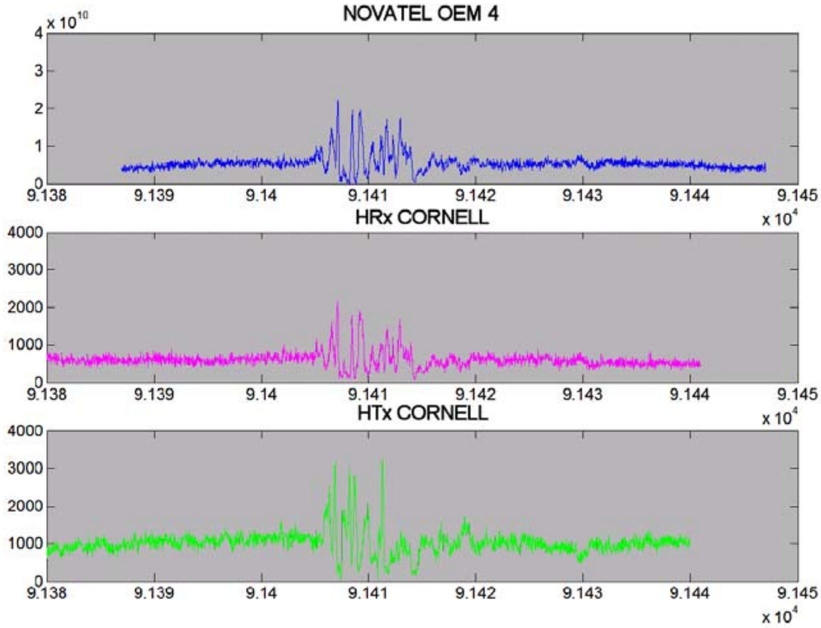

Figure 5: Signal power measurements from the GPS receivers

The velocity of the disturbing structure was computed from the GPS data and the ASC data, using an assumed altitude. The best correlations showed that the fading evident was probably due to a north-east moving arc at an altitude of 85 km, with an eastward velocity component of some 750 – 800 m/s.

4.0 CONCLUSIONS

An investigation into the relationship between loss of signal lock on GNSS receivers located in Northern Scandinavia and ionospheric scintillation during the November 2004 storm has been presented in this paper. Correlation of losses of lock between the three Novatel receivers is quite strong, even over periods as short as 10 minutes. Similarly, the loss-of-lock correlations between the IGS receivers is strong. However, if we correlate the number of losses of lock on the Novatels with the IGS receivers, we find that the correlations are much weaker, indicating that loss of lock is more strongly associated with receiver type.

Three closely located GPS receivers in the high arctic experienced a short period of rapid signal fading during a substorm event. Two of the receivers are of a different manufacturer and are collocated; these showed almost identical fading patterns. Closer examination revealed a time difference between the fading events, from the two receivers of the same type, along a 240 m east-west baseline. This translated into a possible ionospheric structure at 85 km altitude with an eastwards velocity in the order of 750 – 800 m/s. The fading on the GPS signals is thus attributed to a fast-moving auroral source of electron density precipitation that is associated with the aurora.

5.0 REFERENCES

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[5] Blewitt G. An automatic editing algorithm for GPS data, Geophysical Research Letters, Vol. 17, No. 3, pp 199-202, March 1990.

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[7] Atmo Kivelson, Introduction to space Physics, Cambridge University Press 1995.

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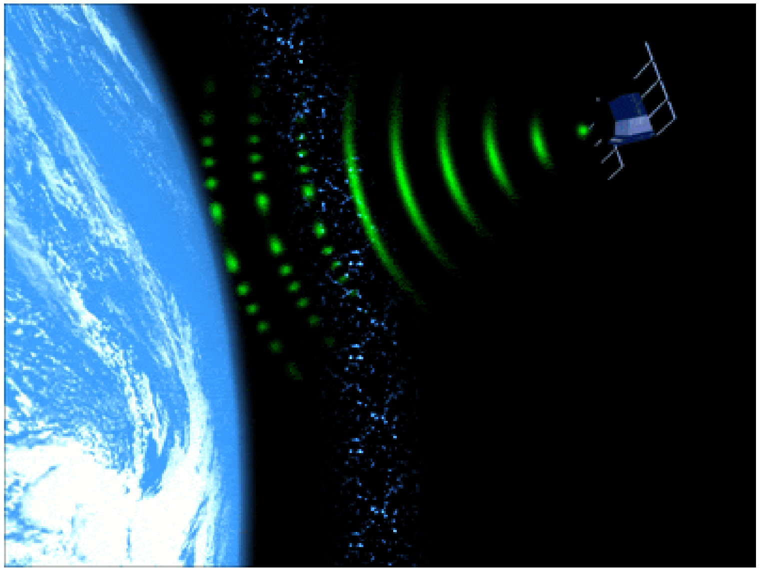
What is scintillation?

- Rapid fluctuations in signal phase and amplitude.
- In Auroral Regions, particle precipitation results in small-scale irregularities in the ionosphere.
- Scintillation happens when signals pass through these irregularities.



Quantified by standard deviation of fluctuations over one minute.
Phase is ‘sigma-phi’ and amplitude is ‘S4’.

Consequences of scintillation

- Can cause GPS receivers to lose lock on signal (‘cycle-slips’).
- Limits availability of carrier-phase measurements.
- Effects can be worse on L2 frequency.

If we can measure scintillation at one location, can we use that measurement as a predictor for when another receiver at another location will lose lock?

Outline

1. Equipment and parameters.
2. Signal fade on very short baseline.
3. Correlations of cycle-slips with sigma-phi and S4 over
   - Short baselines (~ 20 km)
   - Long baselines (~ 200 – 400 km)
4. Correlations of cycle-slips with Kp geomagnetic index.
5. Spatial coverage.
6. Conclusions and future work.

Equipment

Scintillation receivers deployed during summer of 2004.

At each EISCAT site:

- One Novatel GSV4004 measuring phase and amplitude at 50Hz.

At the EISCAT Tromso site:

- Two Cornell receivers measuring amplitude at 50 Hz:
  - One co-located at Heater Receiver (HRx).
  - One at Heater Transmitter (HTx) approx 250 m to west.

All data retrieved and archived at Bath

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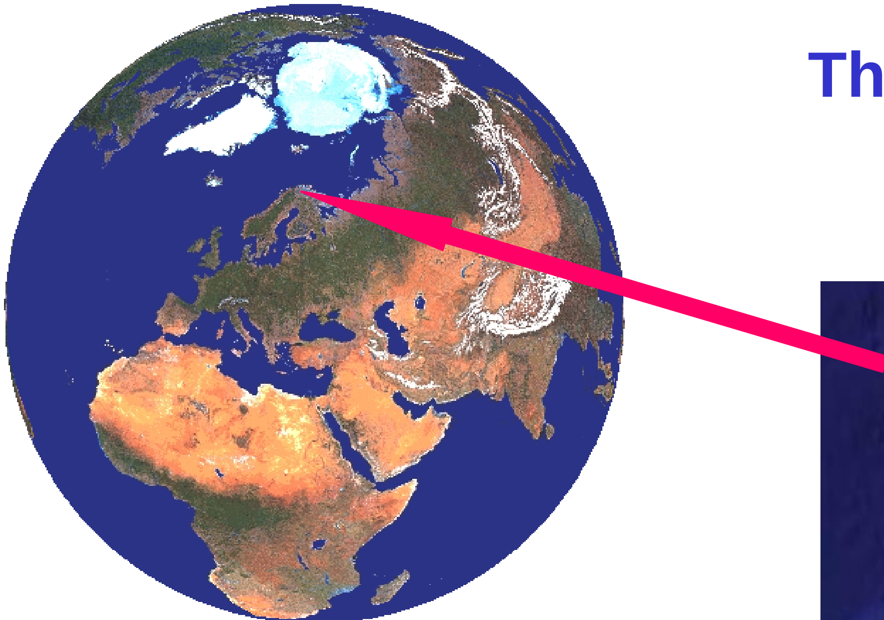
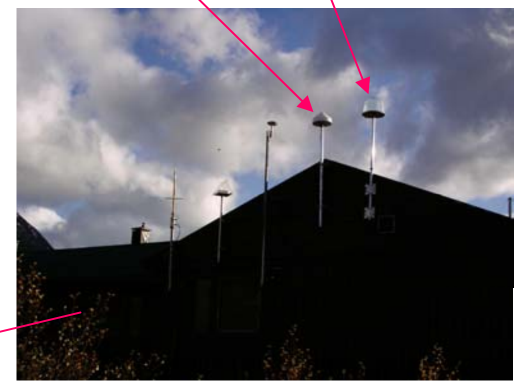


The EISCAT site locations

- Tromso (69.58° N, 19.23° E)
- Kiruna (67.86° N, 20.44° E)
- Sodankyla (67.36° N, 26.63° E)

Cornell

Novatel



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Parameters (1)

- Eight days over November 2004 storm: 7-Nov-2004 to 14-Nov-2004.
- Kp ranged between 2 and 8.
- Elevation mask of 35°.
- Scintillation measured using scintillation receivers at Tromsø, Kiruna and Sodankylä.
- Cycle-slips in phase observation data counted for four IGS receivers: ‘trom’, ‘tro1’, ‘kiru’, ‘soda’.
- Total of L1 and L2 cycle slips on all IGS receiver-to-satellite paths counted over 1, 2, 3, 4, 6 and 8 hours.

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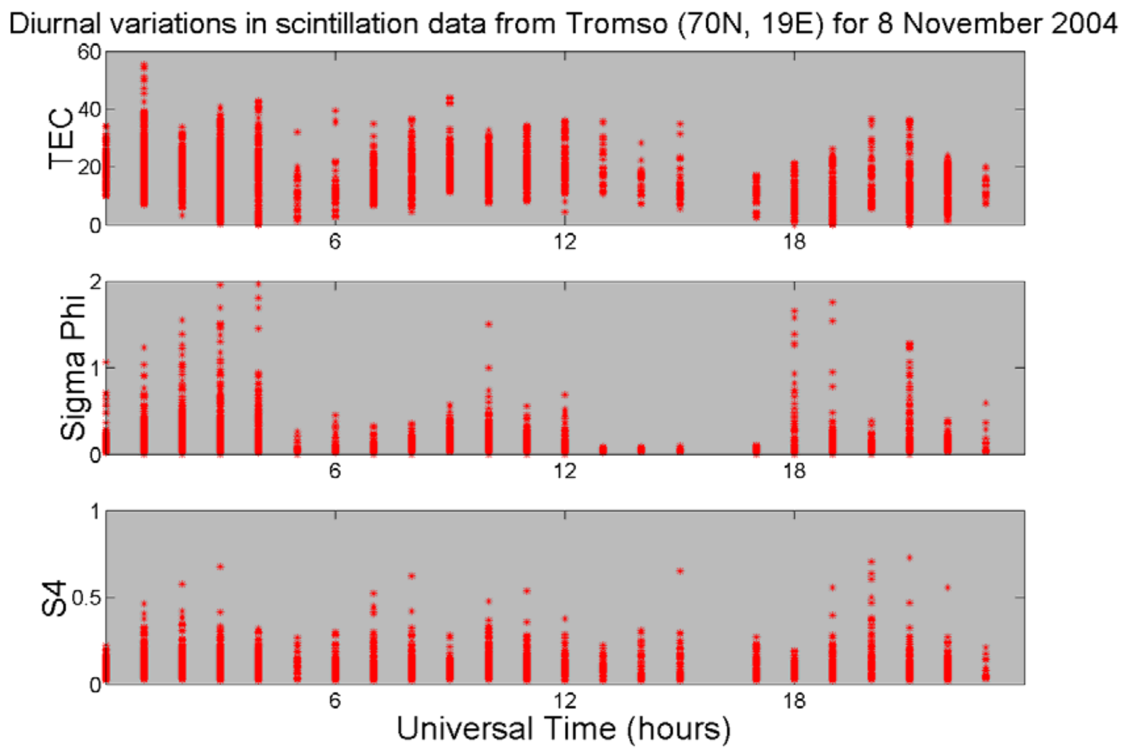
Parameters (2)



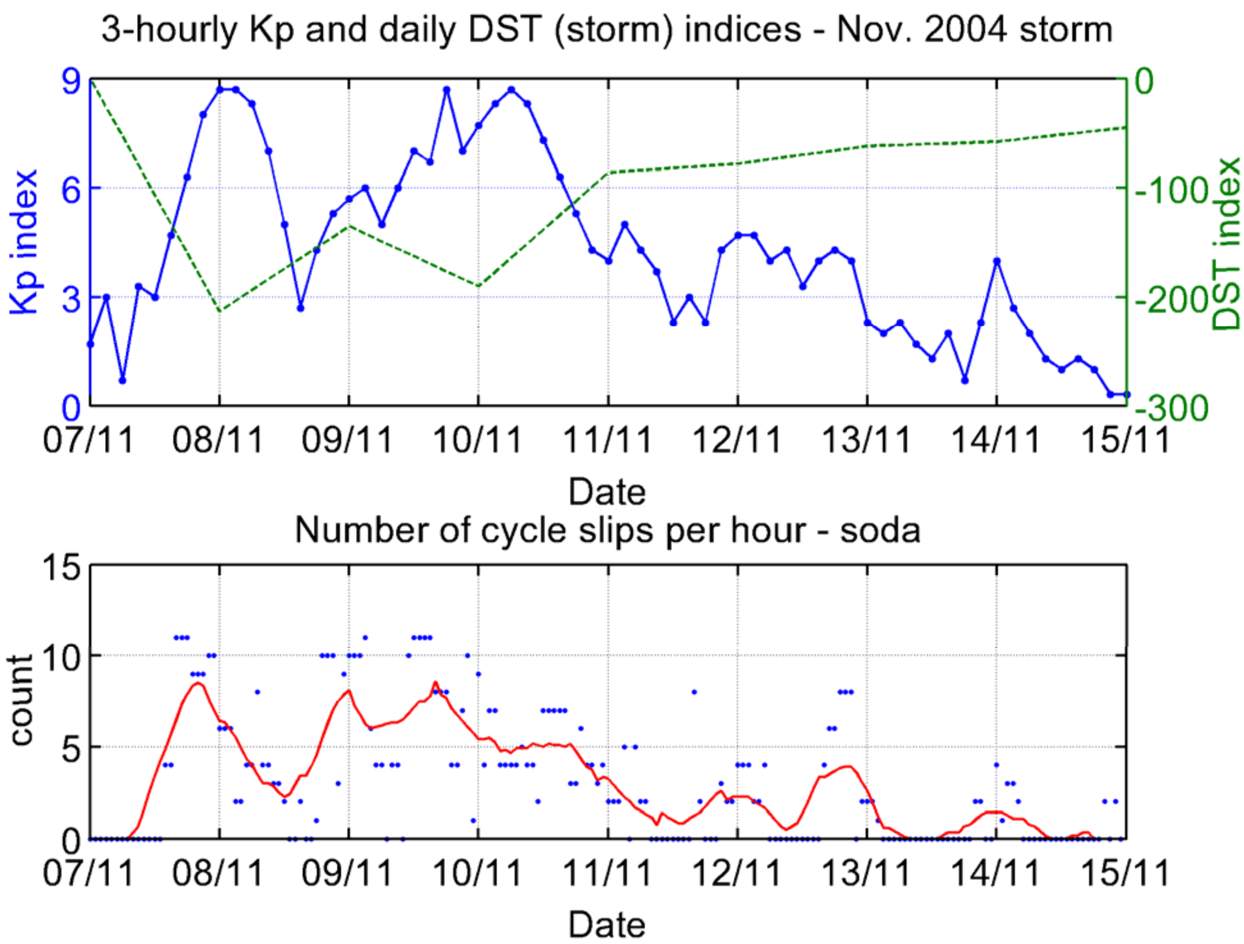
Cycle-slip identification in IGS receivers

1. Form ionosphere-free ('L4') phase combination:

$$\mathrm{L4} = \left(\frac{\Phi_1}{154} - \frac{\Phi_2}{120} \right) \frac{c}{10.23}$$

2. Compute gradient, dL4, of L4.
3. Compute 10-point running median of non-zero values of dL4.
4. Scale running median by a threshold value to allow for noise.
5. Compare dL4 to threshold to find time indices of cycle slips.

Kp index and example count



1. Equipment and parameters.
2. **Signal fade on very short baseline.**
3. Correlations of cycle-slips with sigma-phi and S4 over
   - Short baselines (~ 20 km)
   - Long baselines (~ 200 – 400 km)
4. Correlations of cycle-slips with Kp geomagnetic index.
5. Spatial coverage.
6. Conclusions and future work.

Very short baseline – 250 m

- Recall that the S4 index is an *average over one minute* – hence does not characterise short duration fades.
- Short duration fades are evident in raw amplitude data.
- May be sufficient to cause a receiver to loose lock.
- Three receivers at Tromsø observed a rapid signal fade between 01 & 02 UT on 8-Nov-2004.
- Fade was on the link to GPS PRN05.
- Disturbing structure also observed by All-Sky Camera (557 nm intensity) at Kilpisjärvi, Finland (69.02°N, 20.79°E) .

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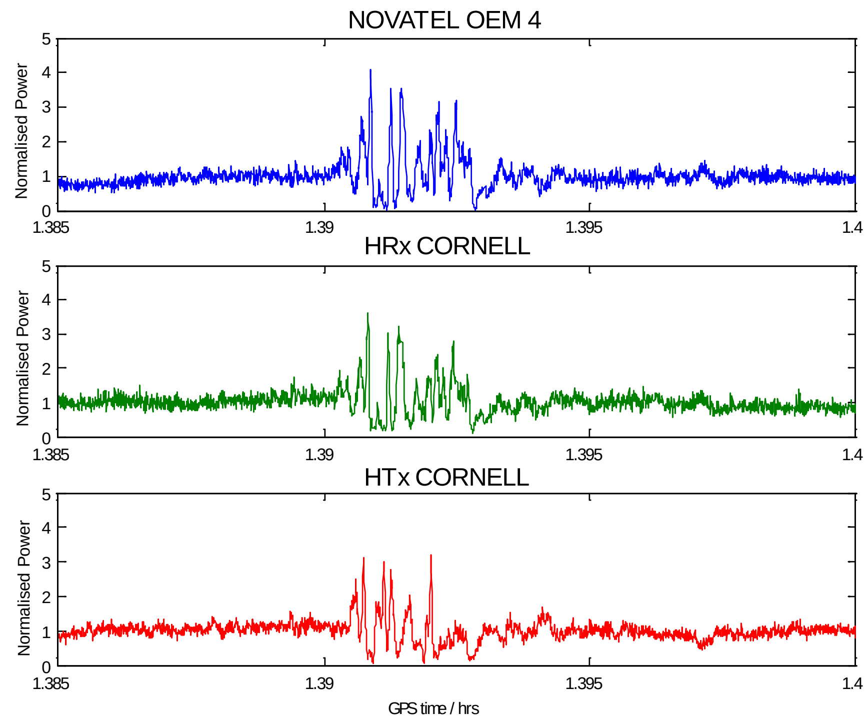
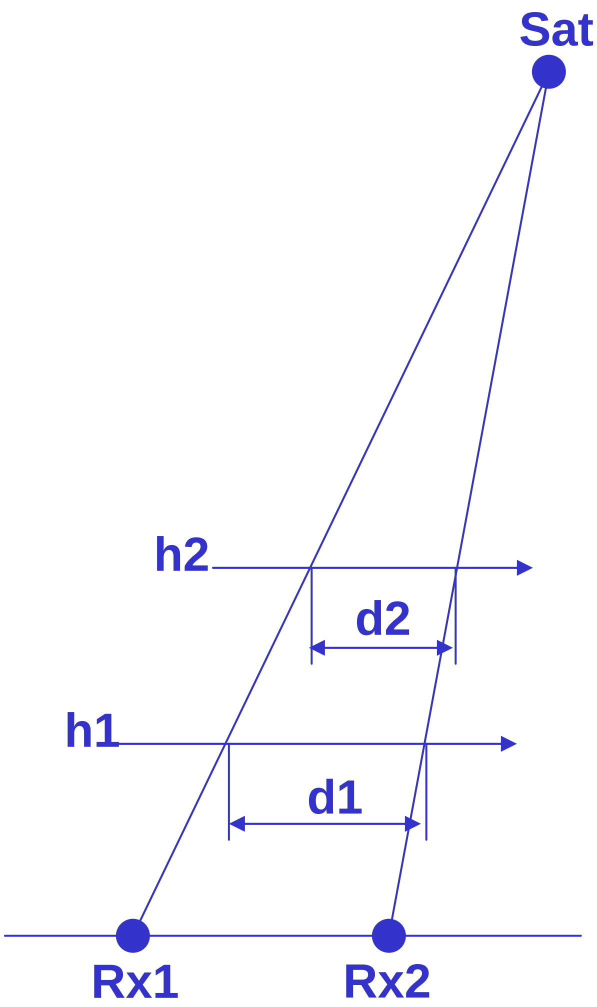
A rapid signal fade



Given an assumed height, the receiver spacing allows the (east-west component of the) velocity of the disturbing structure to be estimated.

Height estimation using GPS receivers



At height **h1**,the disturbance travels distance **d1** in time **t.**

At height **h2**,the disturbance travels distance **d2** in time **t.**

Hence **v1** > **v2** and the velocity decreases with height.

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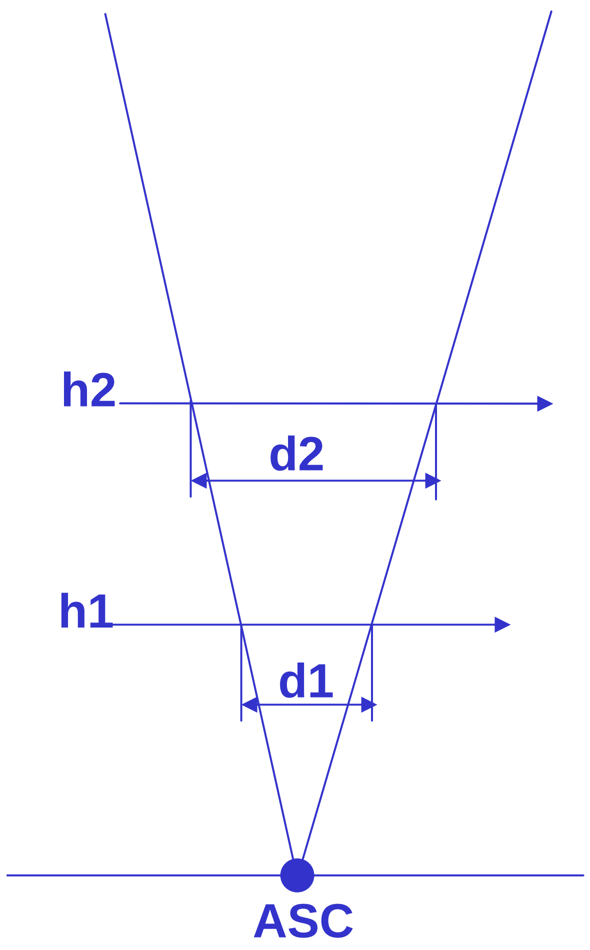
Height estimation using All-Sky Camera



At height **h1**,the disturbance travels distance **d1** in time **t**.

At height **h2**,the disturbance travels distance **d2** in time **t**.

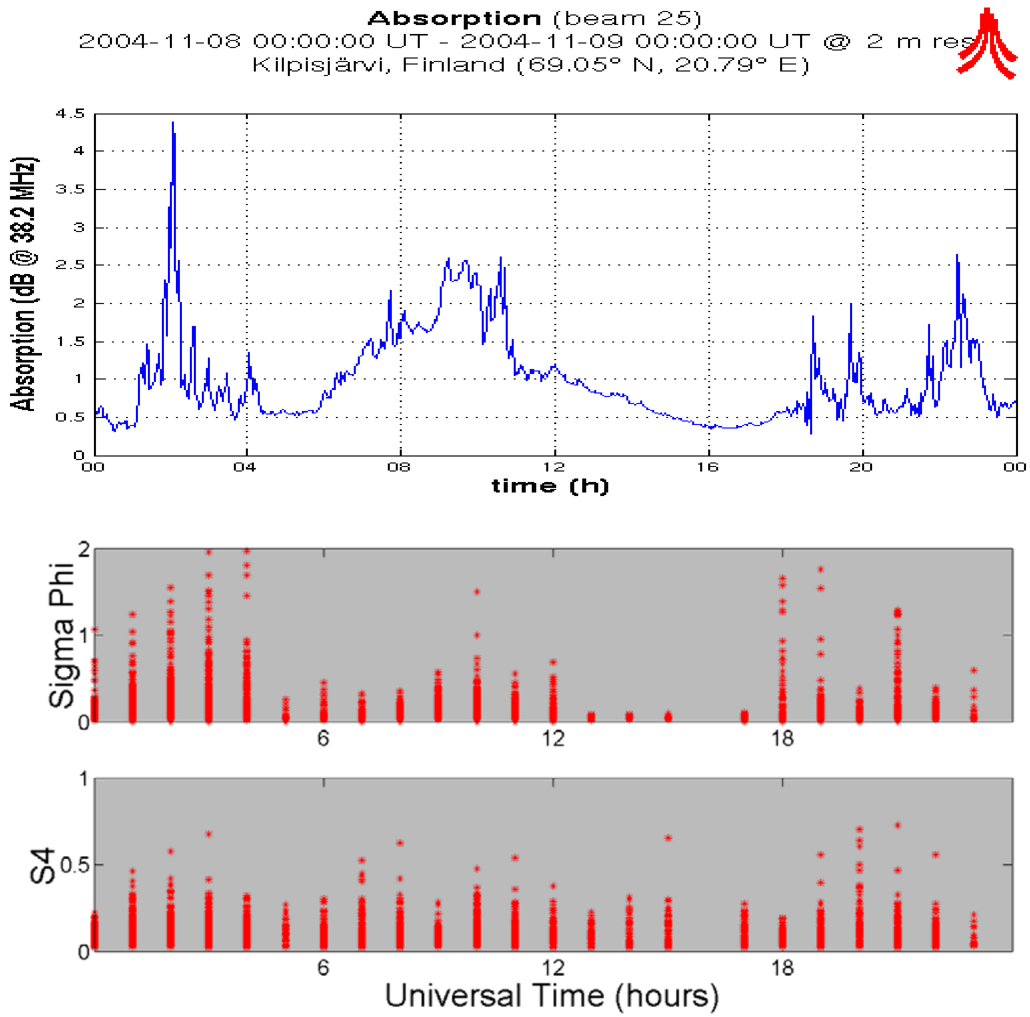
Hence **v1** < **v2** and the velocity increases with height.

So the approximate height of the disturbance will be found when:

v(ASC) ~= v(GPS).

This suggests the disturbance was moving north-eastwards at an altitude of **85 km**, with an eastward velocity component of some **750 – 800 m/s**.

Independent observations by riometer



- Absorption event observed at Kilpisjärvi on 38.2 MHz.
- Supports presence of disturbance in D-region (70 – 90 km)
- Evidence for precipitation related scintillation.

With thanks to Prof. F. Honary, University of Lancaster

Independent observations by All-sky camera

- Mauve cross indicates intersection of receiver to satellite path with a shell at assumed height *at the time of the fade event*.
- The velocity of the structure causing the signal fading is projected with the yellow line.
- An increase in local intensity and movement of the aurora occurs simultaneously with the GPS signal.

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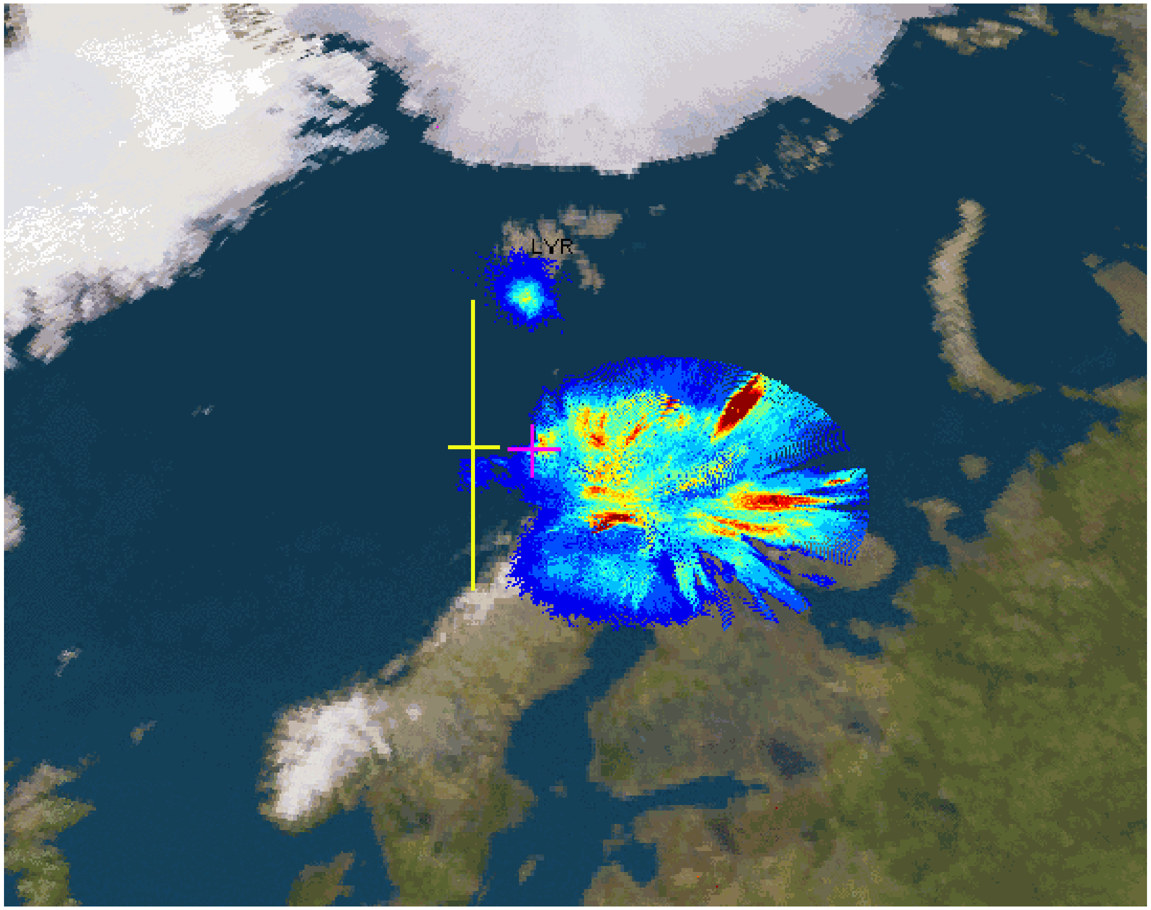
08/11/2004 01:20:00
Aurora height=70.0km, velocity=768.4m/s, bearing=N88.3°E



With thanks to K. Kauristie, Finnish Meteorological Institute

1. Equipment and parameters.
2. Signal fade on very short baseline.
3. **Correlations of cycle-slips with sigma-phi and S4 over**
   - **Short baselines (~ 20 km)**
   - Long baselines (~ 200 – 400 km)
4. Correlations of cycle-slips with Kp geomagnetic index.
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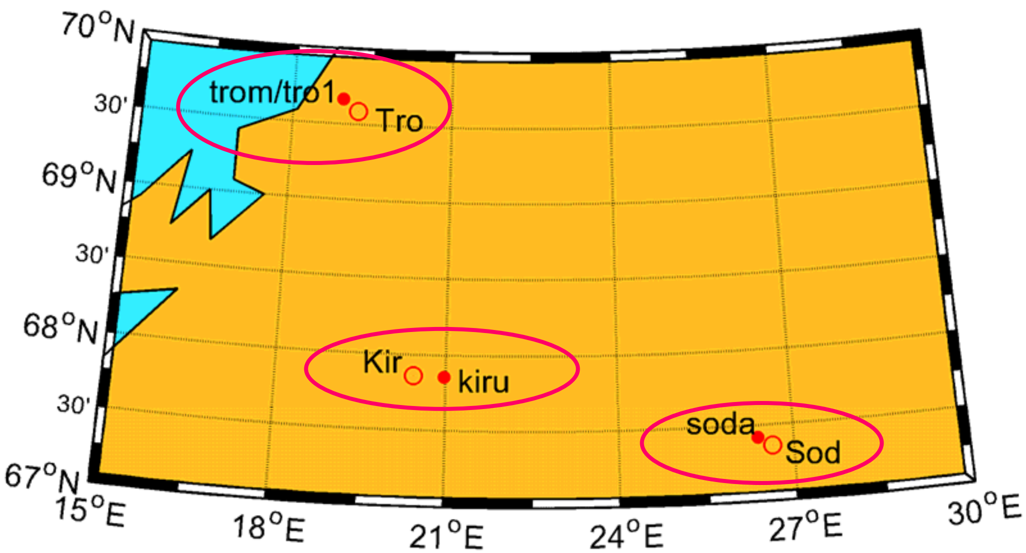
Cycle-slips over short baselines (1)



We have three baselines:

- Tro – trom/tro1: 14 km
- Kir – kiru: 22 km
- Sod – soda: 12 km

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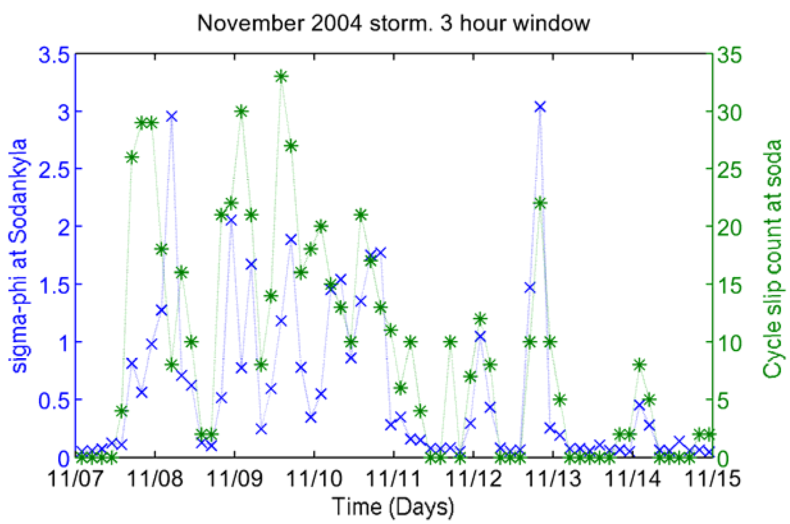
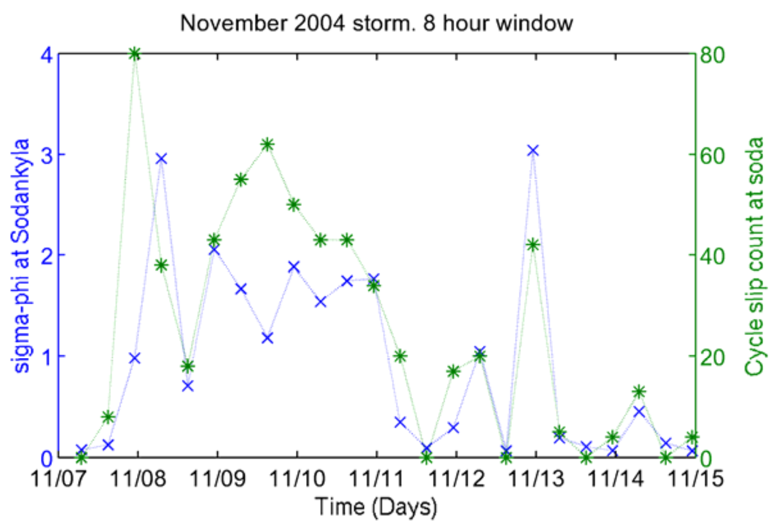
Cycle-slips over short baselines (2)

For each baseline, we plot the **number of cycle-slips** against the **max sigma-phi** in time windows of 1, 2, 3, 4, 6 and 8 hours duration.

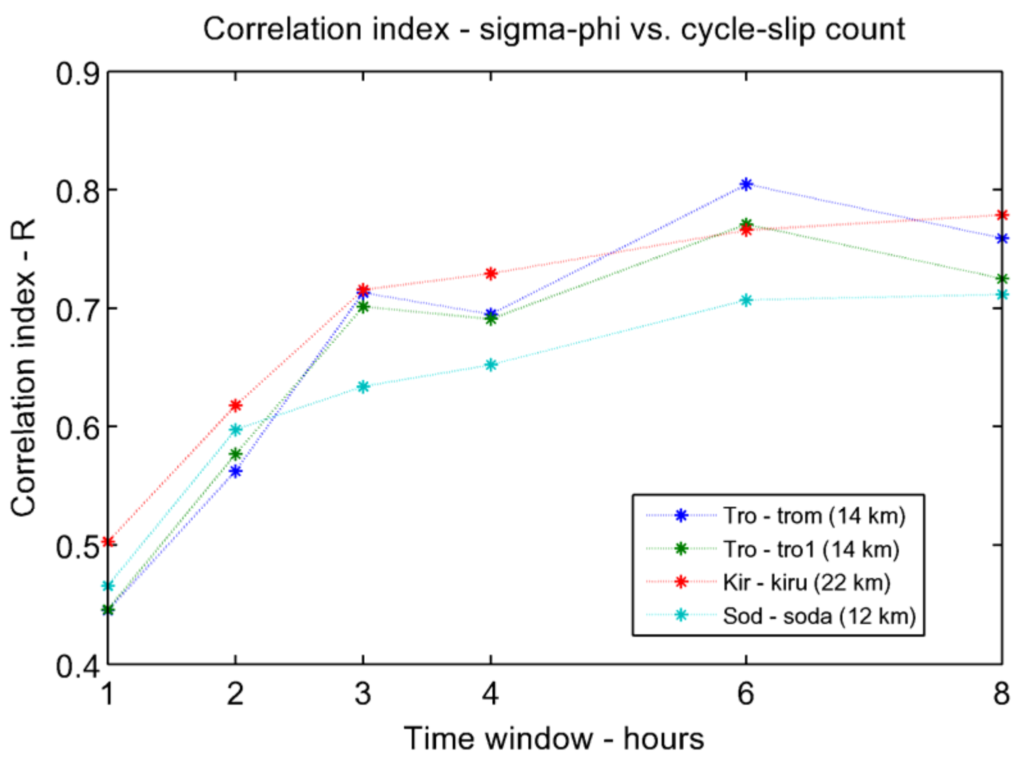
Examples:





We then compute the correlation coefficients for each baseline and each time window.

Cycle-slips over short baselines (3)



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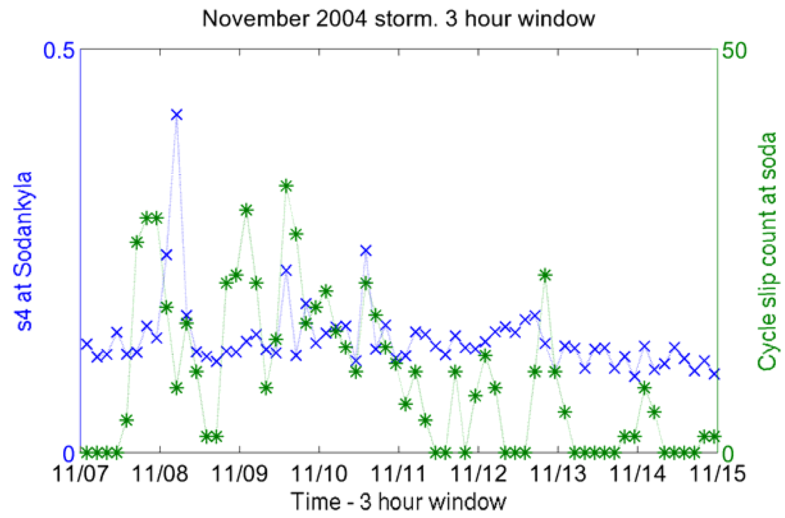
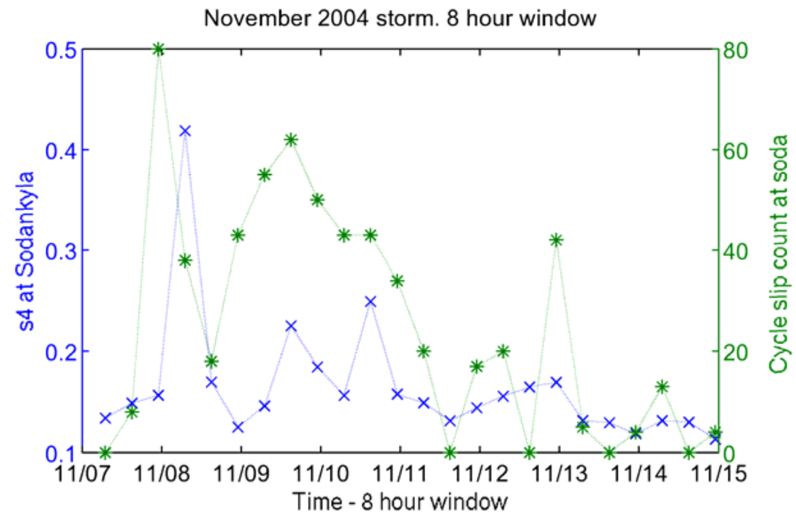
Cycle-slips over short baselines (4)

For each baseline, we plot the **number of cycle-slips** against the **max s4** in time windows of 1, 2, 3, 4, 6 and 8 hours duration.

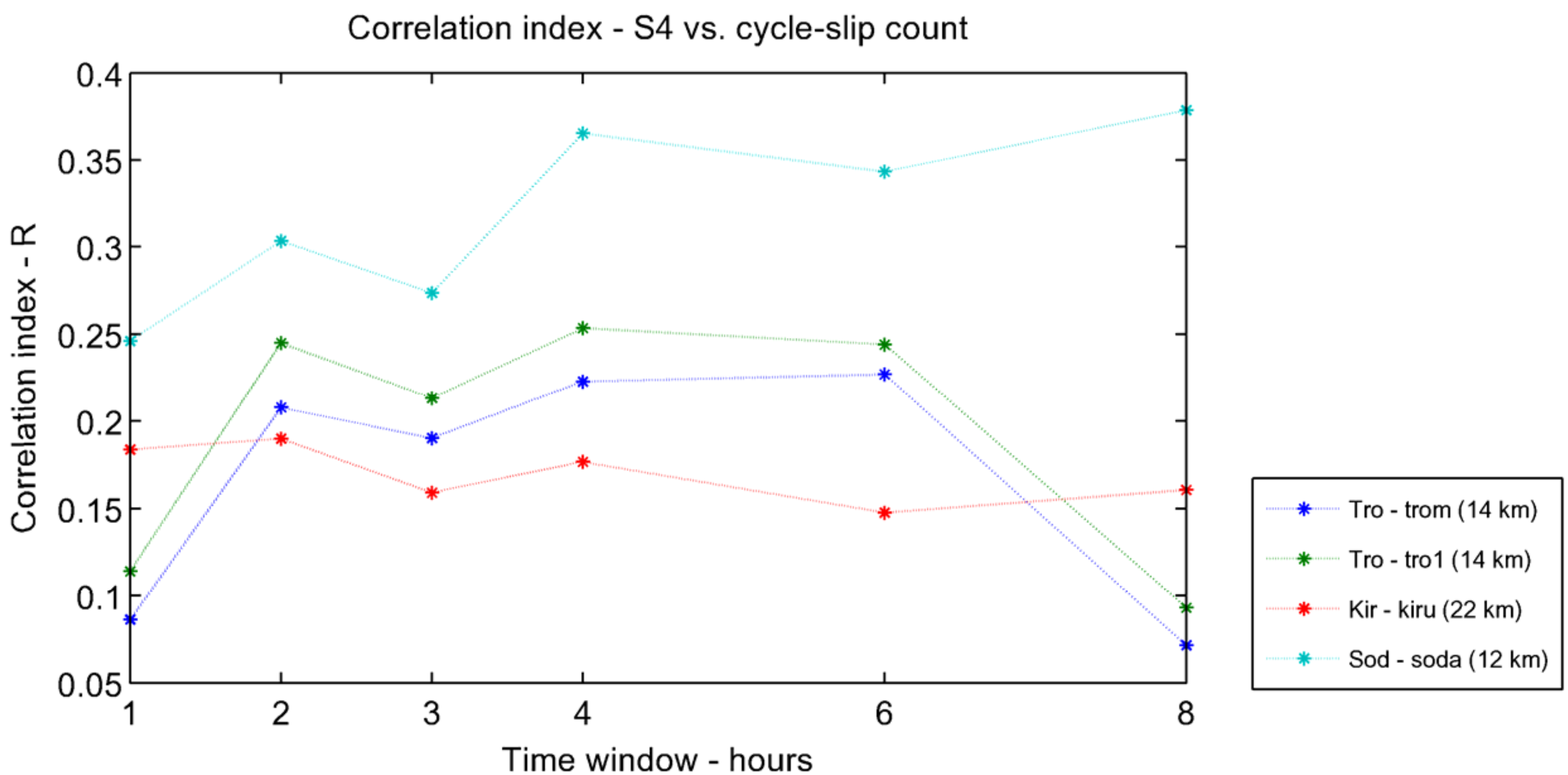
Examples:





We then compute the correlation coefficients for each baseline and each time window.

Cycle-slips over short baselines (5)



Cycle-slips over short baselines - comments

- At longer timescales (> 3 hours), the number of cycle slips is generally more closely correlated with sigma-phi.
- Similar correlation can be observed between cycle slips on either ‘trom’ and ‘tro1’ and sigma-phi measured at EISCAT.
- Correlation between cycle slips and s4 is low - little effect by amplitude scintillation on receiver lock.

1. Equipment and parameters.
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3. **Correlations of cycle-slips with sigma-phi and S4 over**
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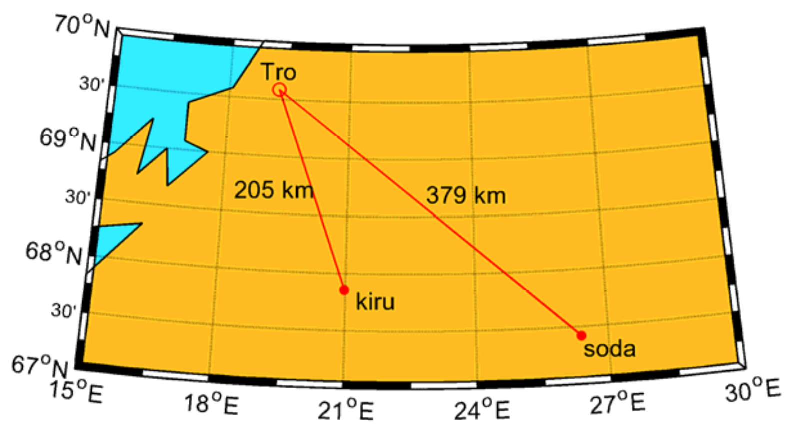
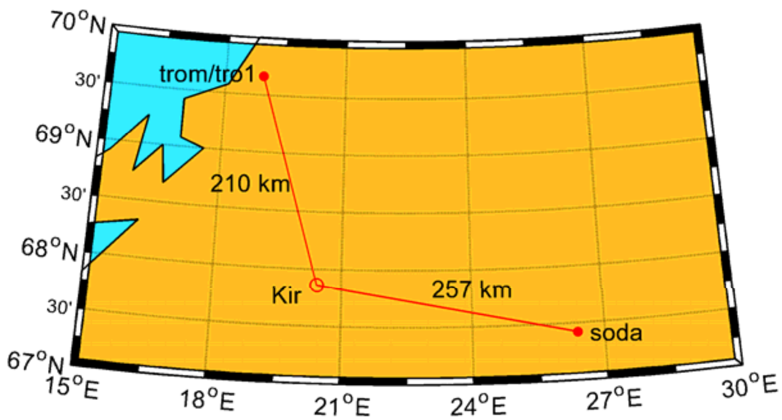
6. Conclusions and future work.

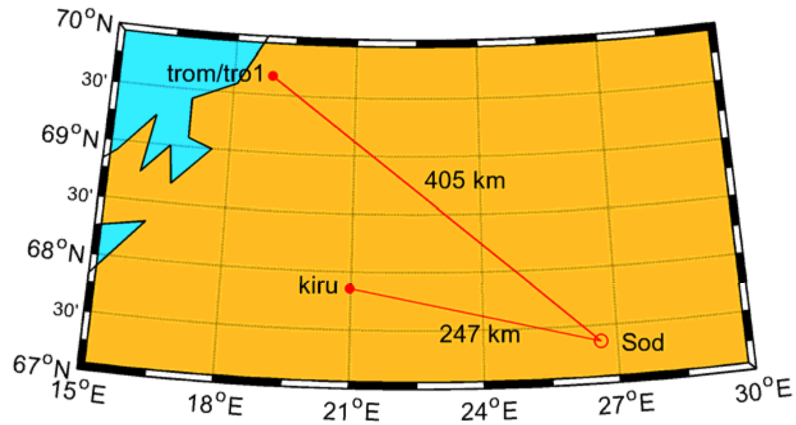
Cycle-slips over long baselines (1)

We have six baselines:

- Tro – kiru: 205 km
- Tro – soda: 379 km
- Kir – trom/tro1: 210 km
- Kir – soda: 257 km
- Sod – trom/tro1: 405 km
- Sod – kiru: 247 km







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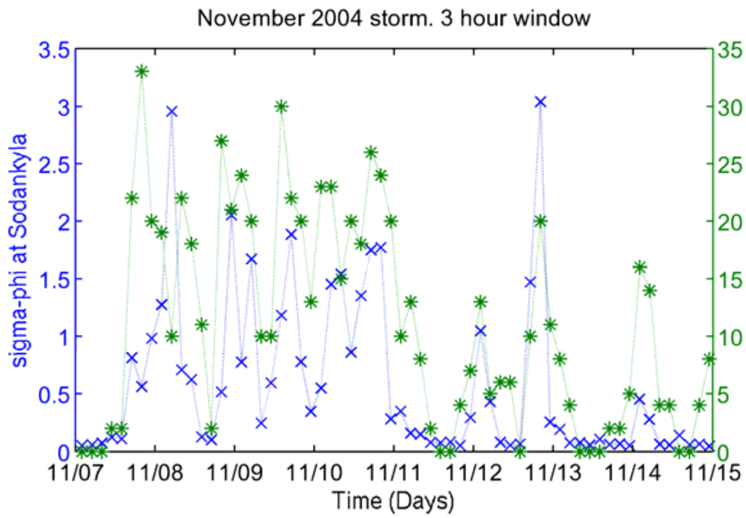
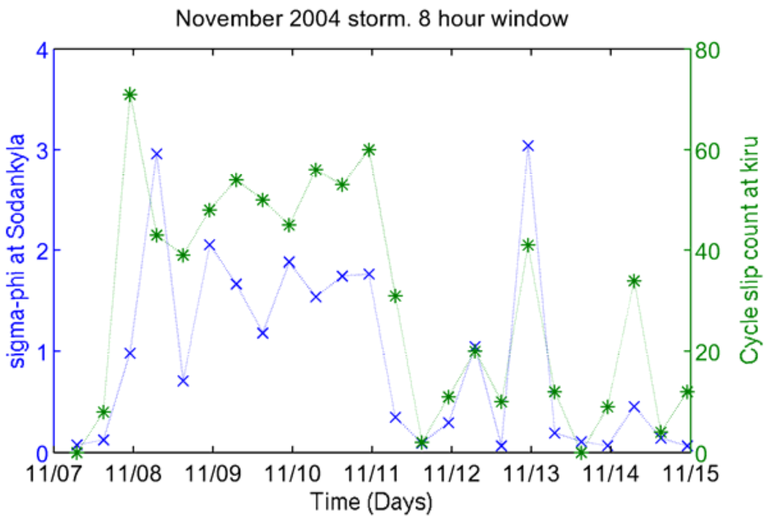
Cycle-slips over long baselines (2)

For each baseline, we plot the **number of cycle-slips** against the **max sigma-phi** in time windows of 1, 2, 3, 4, 6 and 8 hours duration.

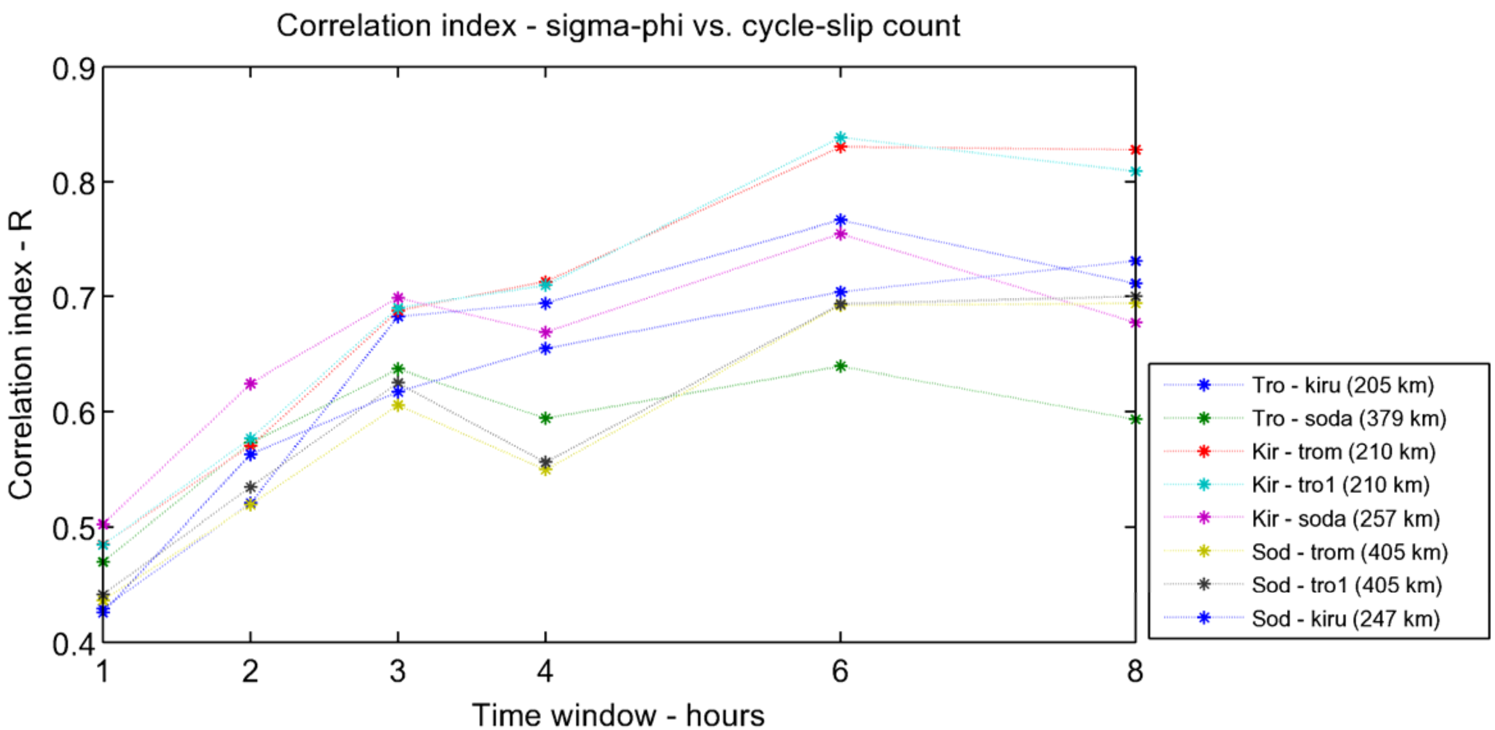
Examples:





We then compute the correlation coefficients for each baseline and each time window.

Cycle-slips over long baselines (3)



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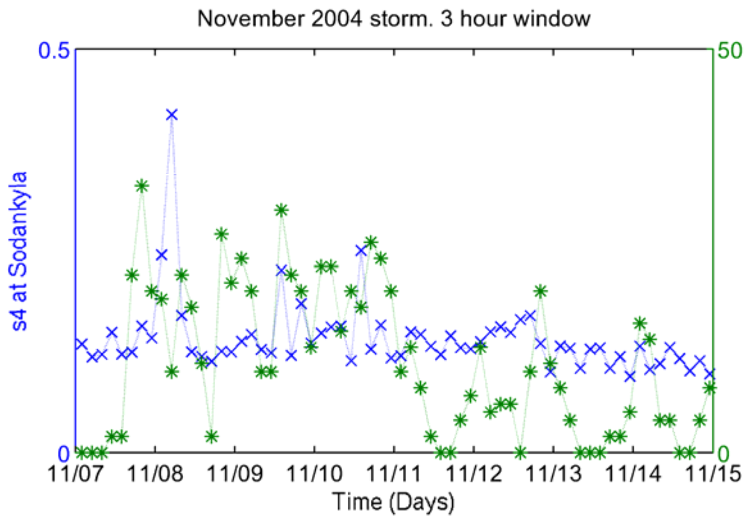
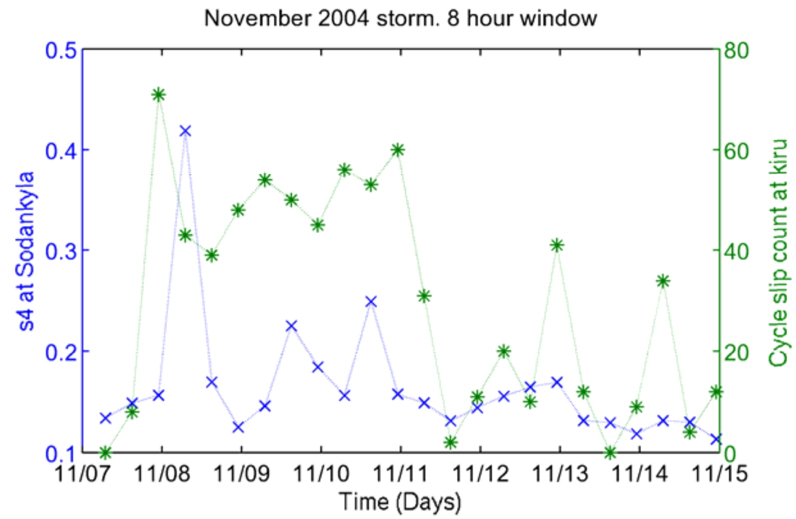
Cycle-slips over long baselines (4)

For each baseline, we plot the **number of cycle-slips** against the **max S4** in time windows of 1, 2, 3, 4, 6 and 8 hours duration.

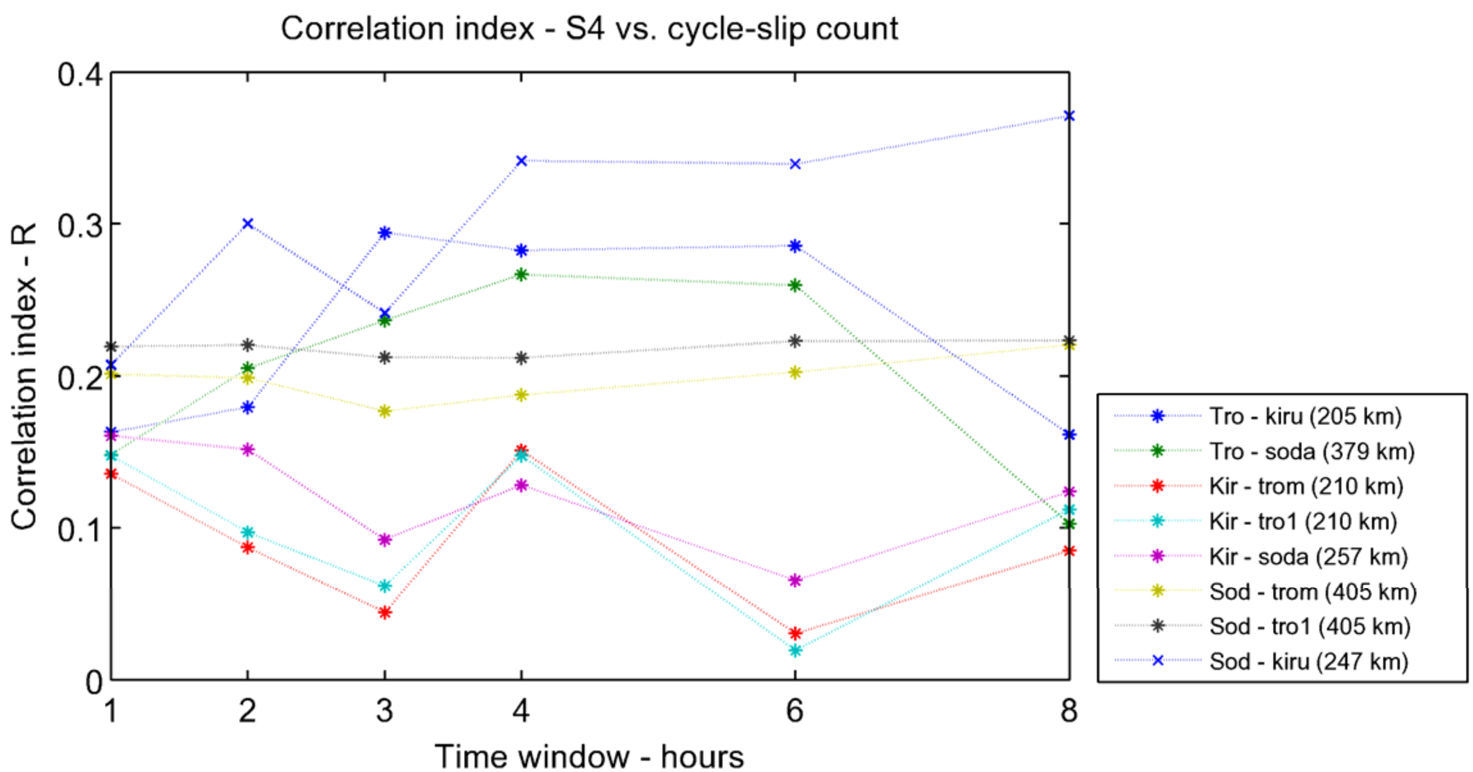
Examples:





We then compute the correlation coefficients for each baseline and each time window.

Cycle-slips over long baselines (5)



Cycle-slips over long baselines -comments

- Correlation between cycle slips and sigma-phi on all baselines drops off below 3 hours.
- Shorter baselines (~200 – 250 km) appear to achieve good correlation at 8 hours, so there would appear to be a relationship between the baseline and cycle-slip/sigma-phi correlation.
- Correlation between cycle slips and S4 is low - little effect by amplitude scintillation on receiver lock, probably due to lack of large S4.

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1. Equipment and parameters.
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   - Long baselines (~ 200 – 400 km)
4. **Correlations of cycle-slips with Kp geomagnetic index.**
5. Spatial coverage.
6. Conclusions and future work.

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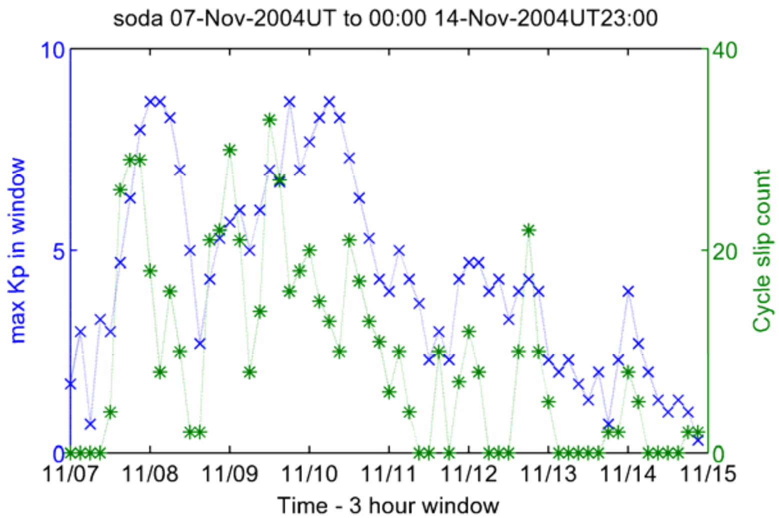
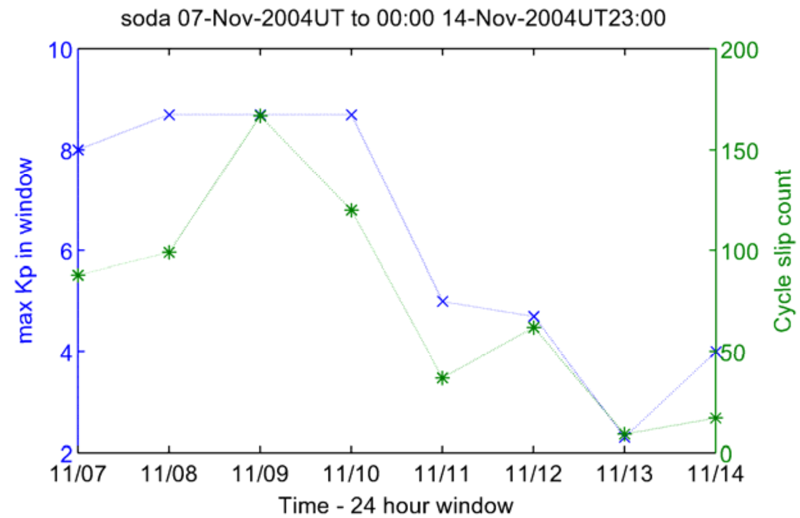
Cycle-slips and geomagnetic Kp index (1)

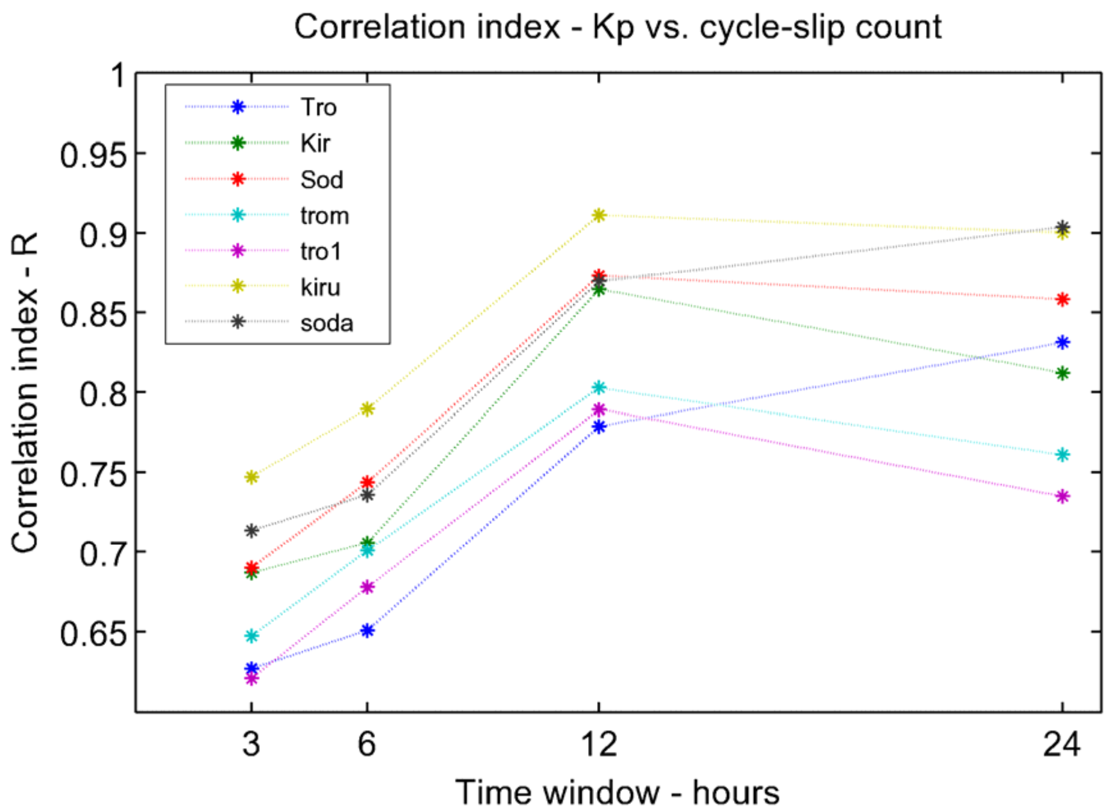
We also plot the **number of cycle-slips** against the **max Kp index** in time windows of 3, 6, 12 and 24 hours duration, and compute the correlation coefficients.

Examples:





Cycle-slips and geomagnetic Kp index (2)



Cycle-slips Kp index -comments

- The correlation between cycle slips and Kp index is good at all timescales.
- As a predictor of loss of lock, Kp may be more reliable than sigma-phi.

1. Equipment and parameters.
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4. Correlations of cycle-slips with Kp geomagnetic index.
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6. Conclusions and future work.

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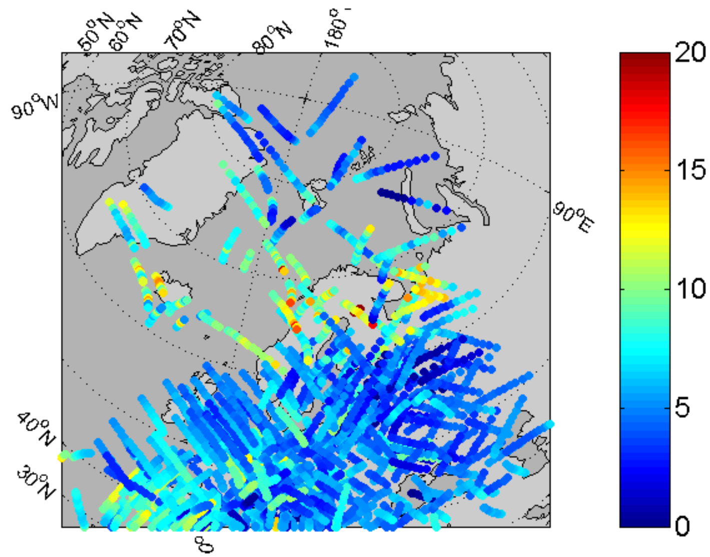
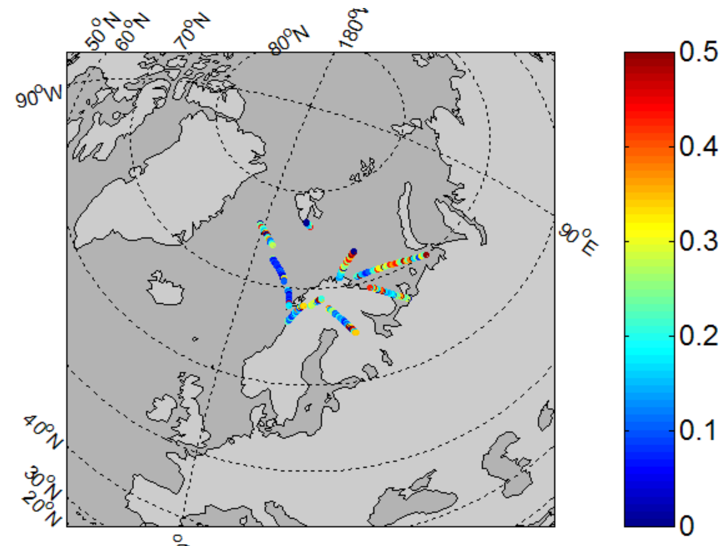
Spatial coverage of plasma



08-Nov-2004 02:00 BIAS CORRECTED VTEC



Sigma phi 8-11-2004-2 UT

- Spatial scales of plasma distribution are very large.
- Events seen by one receiver would not necessarily be seen at another receiver more than a few hundred metres away.

Conclusions

- On a very short baseline (250 m) a rapid fading event was identified on mulitple receivers – appeared to coincide with an auroral arc.
- Riometer data appears to good evidence for precipitation related scintillation at D-region heights (~90 km).
- On both short (~20 km) and long (~200 km) baselines, the number of cycle slips correlates with sigma-phi better on timescales > 3 hours.
- It appears that, for larger baselines (~400 km) correlation falls off.
- For a given receiver, the number of cycle slips correlates quite well with the geomagnetic Kp index.
- The receiver type will have an influence on the number of cycle slips recorded.

Acknowledgements

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